Advancement of Software Configurable Optical Test System

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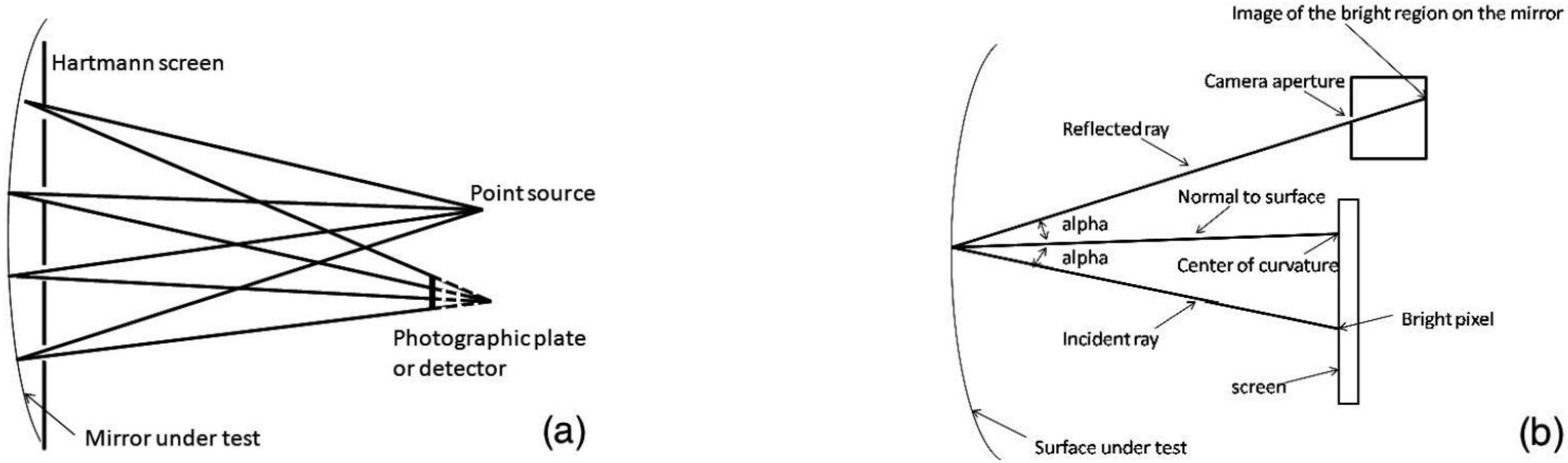
Outline

1. Introduction
2. Basic principle of the SCOTS
3. Experiment results comparing with the results from interferometric tests
4. SCOTS in IR
5. Measuring lens system with SCOTS
6. Summary

1. Introduction

A software configurable optical test system (SCOTS) based on the geometry of the fringe reflection was developed for rapidly, robustly, and accurately measuring large, highly aspherical shapes such as solar collectors and primary mirrors for astronomical telescopes. The SCOTS test can be understood as a Hartmann test in a reverse way. In its simplest configuration, all that is needed to perform the test is a laptop computer with a built-in camera. The laptop illuminates the test surface with a light pattern on the LCD screen and uses the reflected image to determine the surface gradients.



(a) a Hartmann test (b) the SCOTS ---Point illumination

Ref: P. Su et.al. Applied Optics Vol. 49, No.23 p4404-4412 (2010)

1. Introduction

1. The Slope Test has a long history in optical testing, detect lateral displacements of the rays by blocking out or modifying these displaced rays:
The knife edge method was introduced by Foucault in the middle of 19th century. Other developments includes the wire test, the Ronchi test, the Hartmann test (1900), Shack-Hartmann test etc.

2. Reflection deflectometry

1) Ligtenberg introduced the reflection moire method for the determination of moments in small slab models (1954).
2) Reflection grating method introduced by R. Ritter simplified the test for slope measurement using one grating and its image (1983).
3) D. Perard (1997) – structured lighting reflection technique
   R. Hofling (2000)- Phase reflection
   M. Knauer (2004)- Phase Measuring Deflectometry

Using digital screen, phase shifting calculation, calibrating geometry, understanding test theoretical limit, stereo deflectometry--- solve the problem of measuring specular surface for the industry 3D measurement application such as car window, car body, progressive eyeglasses etc.

3. SCOTS for precision of optics (P. Su 2010)

The specific hardware and algorithms optimized for measuring optical surfaces and systems, utilizing the geometry to achieve high-performance results with loose tolerances.

2. Principle

$$w_x(x_m, y_m) = \frac{\dfrac{x_m - x_{\text{screen}}}{d_{m2\text{screen}}} + \dfrac{x_m - x_{\text{camera}}}{d_{m2\text{camera}}}}{\dfrac{z_{m2\text{screen}} - w(x_m, y_m)}{d_{m2\text{screen}}} + \dfrac{z_{m2\text{camera}} - w(x_m, y_m)}{d_{m2\text{camera}}}}$$

$$w_y(x_m, y_m) = \frac{\dfrac{y_m - y_{\text{screen}}}{d_{m2\text{screen}}} + \dfrac{y_m - y_{\text{camera}}}{d_{m2\text{camera}}}}{\dfrac{z_{m2\text{screen}} - w(x_m, y_m)}{d_{m2\text{screen}}} + \dfrac{z_{m2\text{camera}} - w(x_m, y_m)}{d_{m2\text{camera}}}}$$

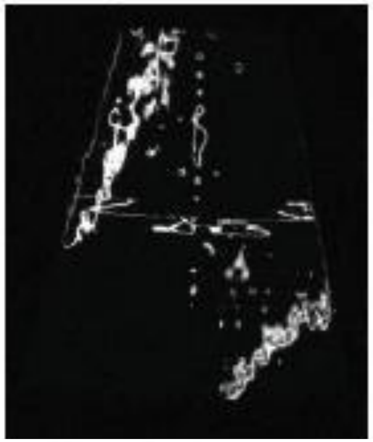
Knowing coordinates of the display screen, the camera and the test mirror, surface slopes of the test mirror can be obtained by triangulation. Surface sag can be calculated by the model fitting or zonal integration methods.

Mapping between screen coordinates and mirror coordinates need to be determined for the triangulation calculation. --- phase unwrapping

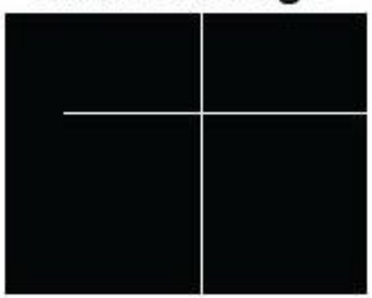
2. Principle

Line Scanning (line illumination)

Image at CCD



Monitor image



Each time a line on the screen are lit up for illumination. Bright regions of the mirror image are lit up by a line of pixels which have the same x or y coordinates in screen space.

Phase unwrapping is done in time domain and is robust. Phase values are calculated by centroiding.

$$x_{\text{screen}} = \frac{\sum\limits_{i \in \text{ESP}} x_i I_i}{\sum\limits_{i \in \text{ESP}} I_i}, \quad y_{\text{screen}} = \frac{\sum\limits_{i \in \text{ESP}} y_i I_i}{\sum\limits_{i \in \text{ESP}} I_i}$$

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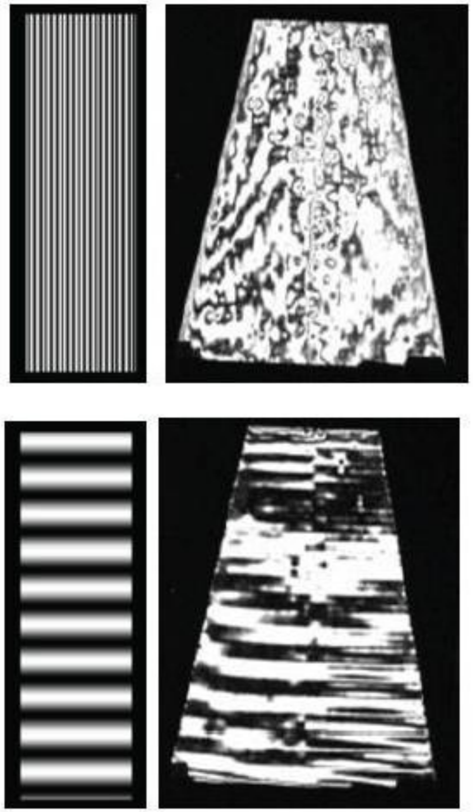
2. Principle

Fringe reflection
(Fringe illumination)



Sinusoidal fringes are used as illumination patterns.

Phase unwrapping is done by an intensity coding.

Phase values are calculated by the synchronous detection.

$$I = a + b\cos(2\pi r/p + t).$$

p is the period of the fringe on the display, r is the screen coordinate of the illuminating pixel

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2. Principle

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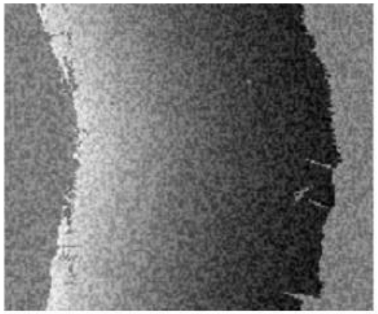
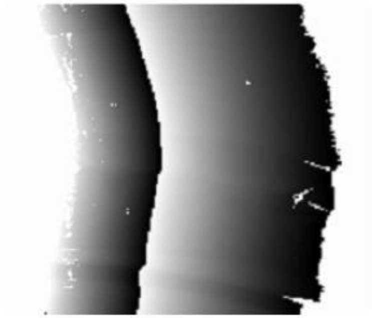
$$\phi(x,y) = \tan^{-1}\left[\frac{-\sum I_i \sin(\delta_i)}{\sum I_i \cos(\delta_i)}\right]$$

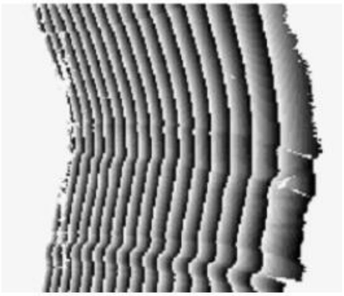
$$\delta_i = i2\pi/N; \qquad i = 1,\ldots,N$$

Phase can be calculated with N step phase shifting algorithm

Multiple-period methods may need to used for solving phase ambiguities.







Ref [1]: W. Osten, et. al. ,Proc. SPIE 2860, 2-13 (1996)
Ref [2]: W. Juptner, et. al. ,Pro. SPIE 7405, 740502 (2009)

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2. Principle

Test measurement coordinates are calculated from the mapping between camera image coordinates to test surface coordinates.

The mapping accuracy are determined by the accuracy of the camera distortion calibration and knowing of the position geometry.

Mapping sensitivity: For off-axis setup, the SCOTS measures test surface departures from an elliptical surface. Least mapping sensitive is obtained when the surface is close to an elliptical shape. Mapping sensitivity is propositional to the second derivative of the surface departures.

Transverse ray aberration (surface gradients): calculated from display screen coordinates and knowing of the position geometry.

Camera Pupil aberration: affect the slope measurement.

2. Principle

Test spatial resolution: imaging and diffraction effect

$$\delta x = \frac{\lambda}{\sin u}.$$

Tradeoff between spatial resolution and slope sensitivity:

$$\tan \delta\alpha \cdot \delta x = \frac{\pi\,\lambda}{Q}$$

Test dynamic range: limited by the size and angular range of the screen display

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Ref [1]: M. Knauer, et. al. ,Proc. SPIE 5457, 366-376 (2004)

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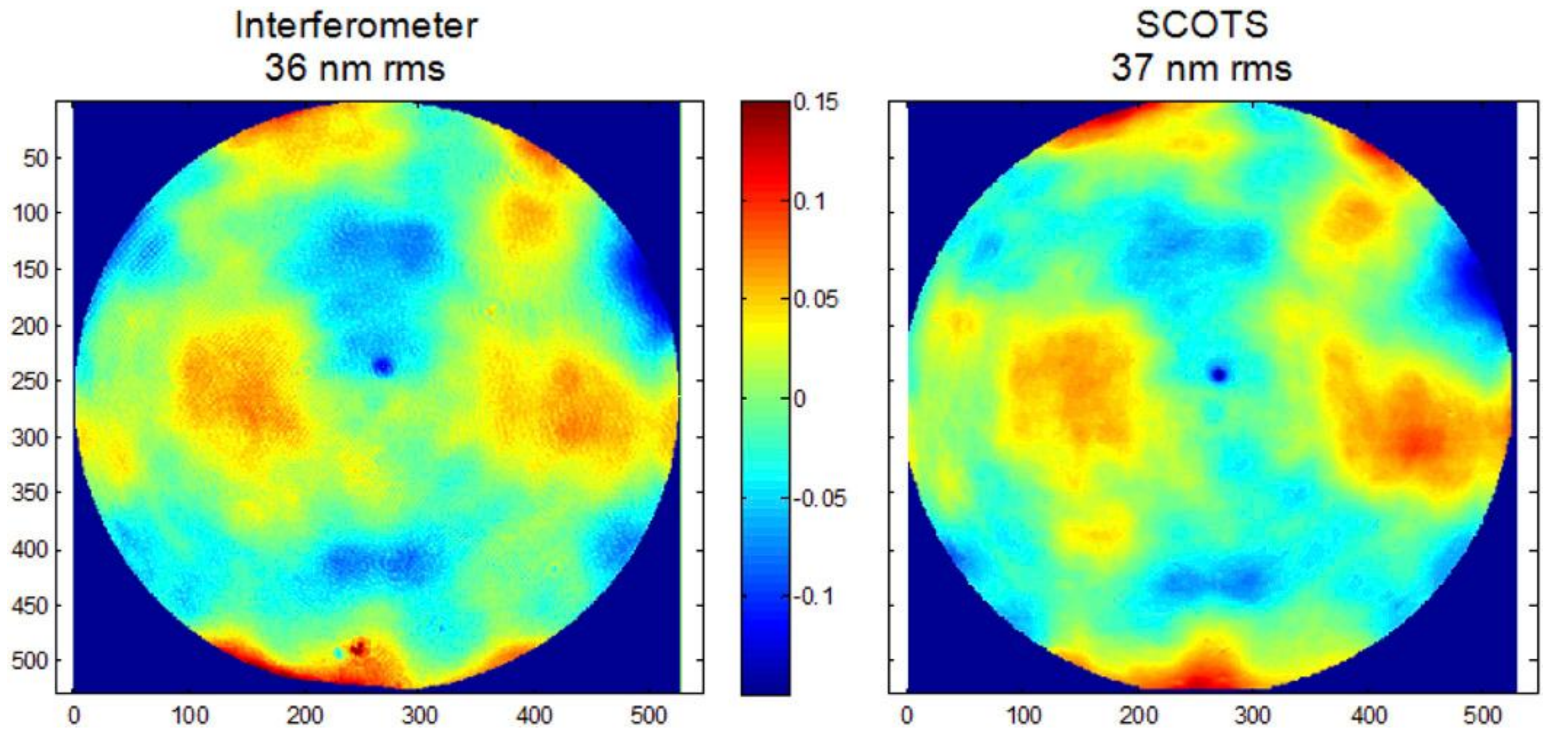
3. SCOTS –measuring 4m fold sphere



Low order terms of astigmatism, coma, spherical and trefoil have been removed from both topographic maps. Two tests done at same time.
Color scale in micrometers

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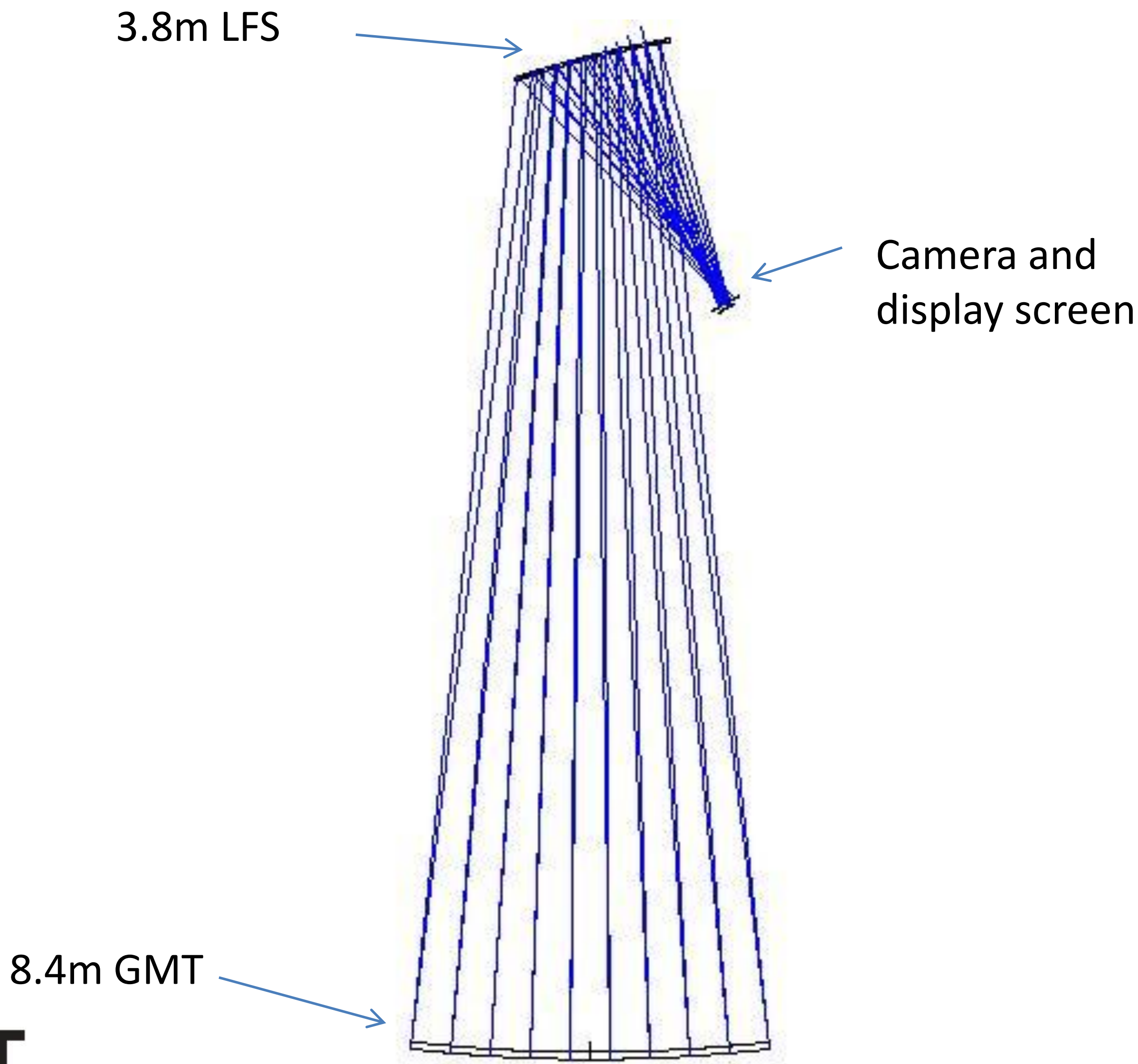
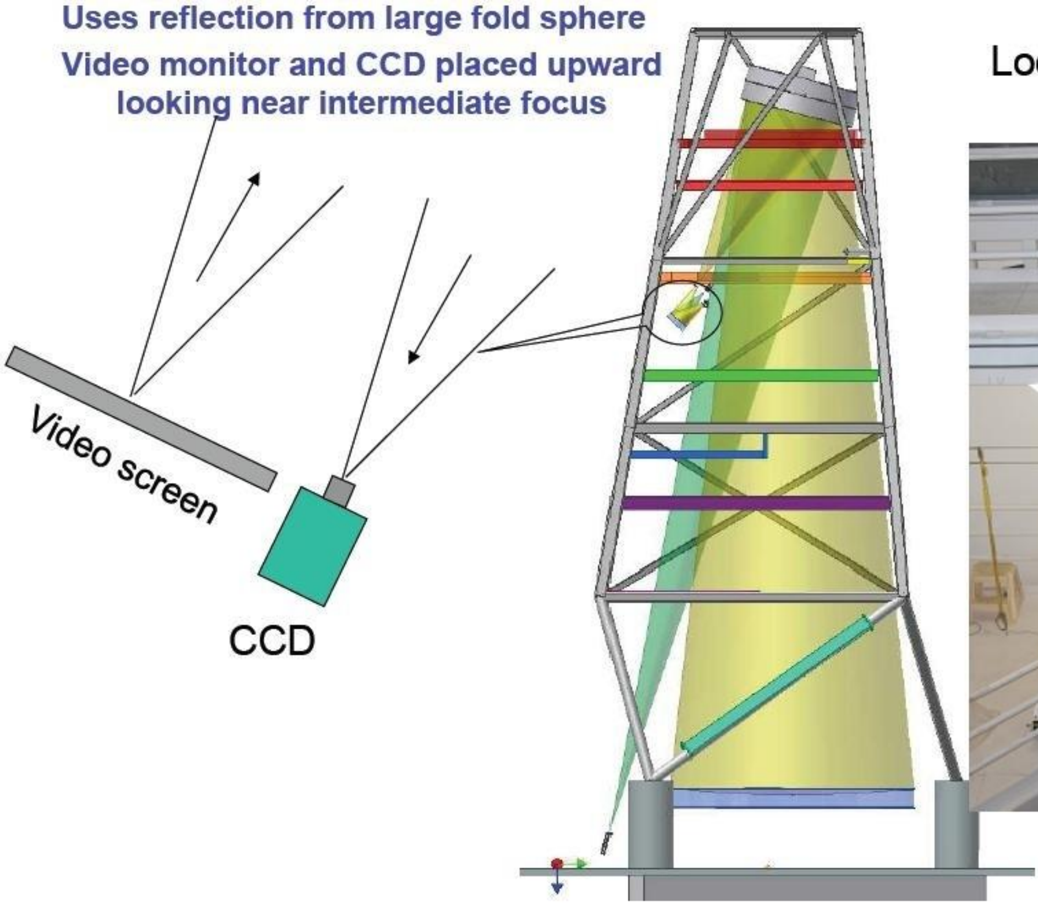
3. SCOTS –measuring 8.4 GMT segment

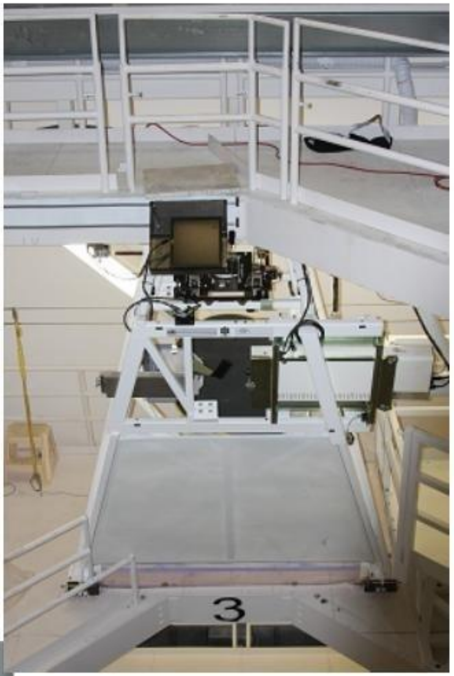


Test design

3. SCOTS –measuring 8.4 GMT segment

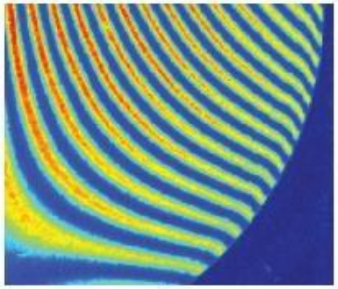


Looking down at Sam and SCOTS

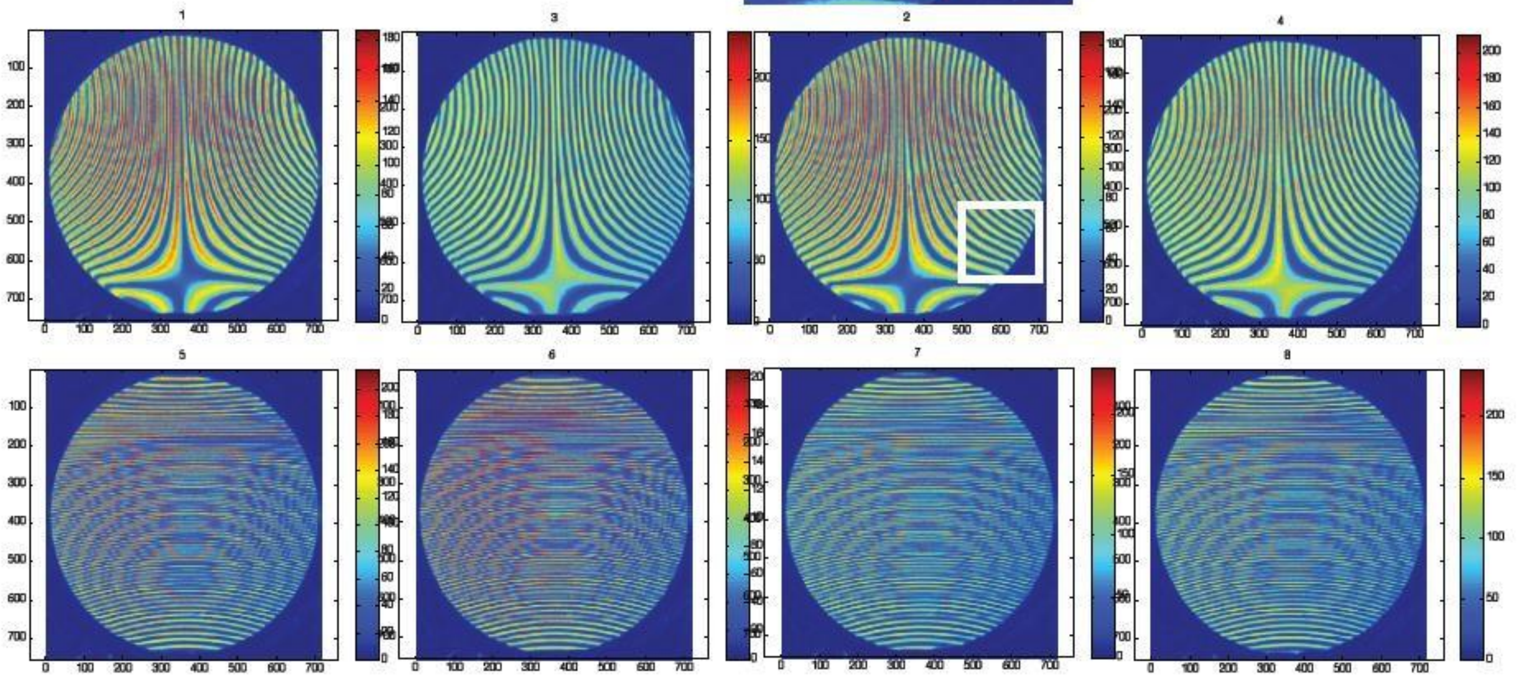


Experiment setup

3. SCOTS –measuring 8.4 GMT segment



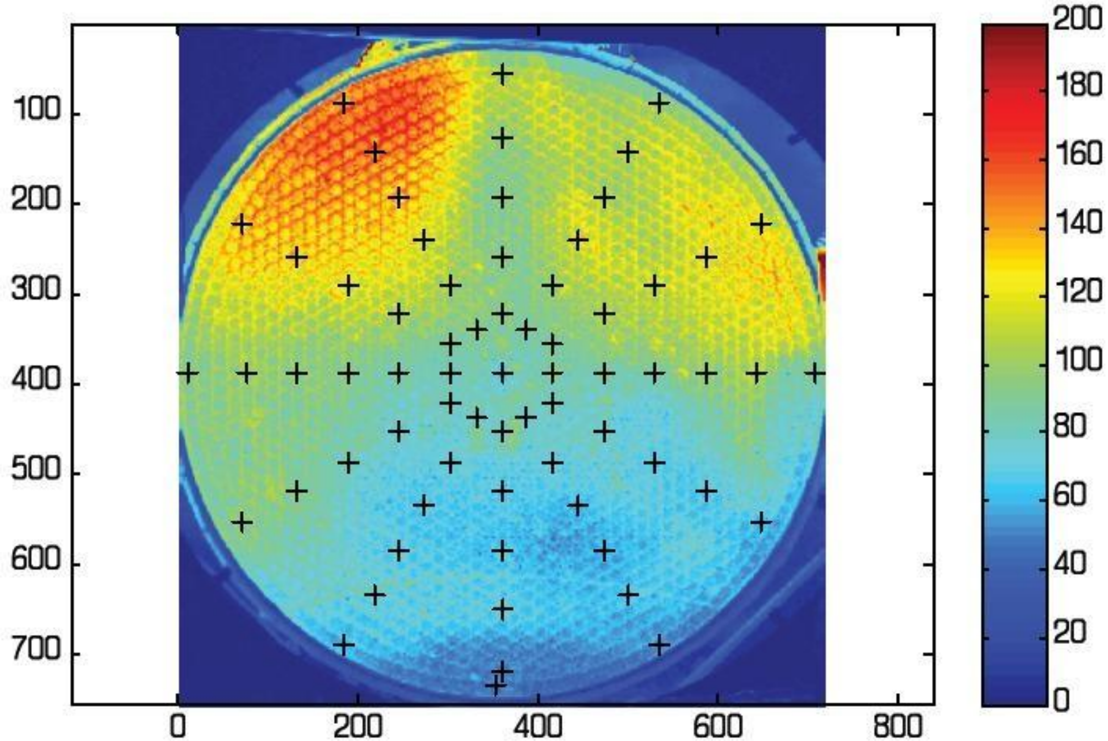
Slope errors at edge are apparent



Fringe data

3. SCOTS –measuring 8.4 GMT segment

- Distortion calibration using cores for reference
- Uses raw image of mirror as taken with the lights on.



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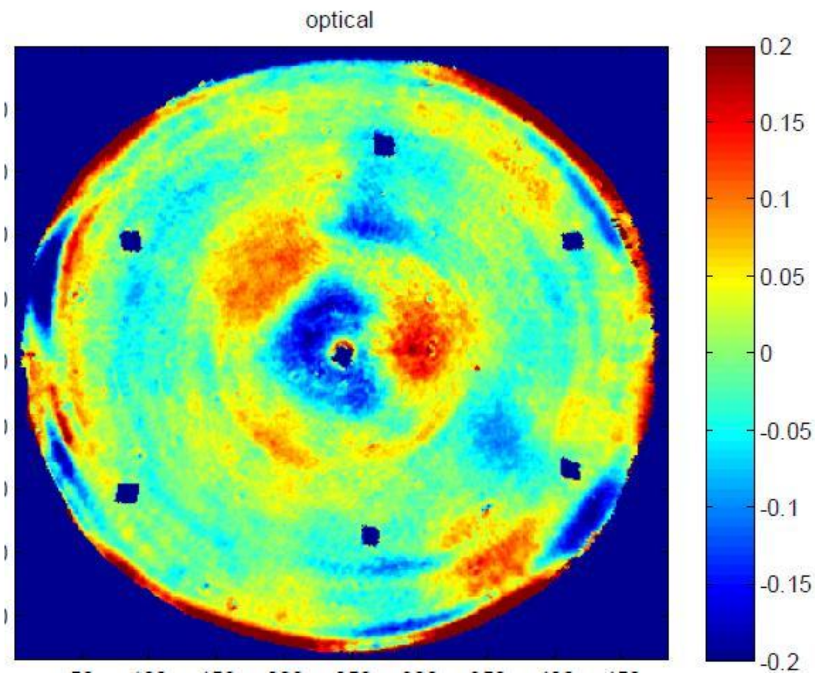
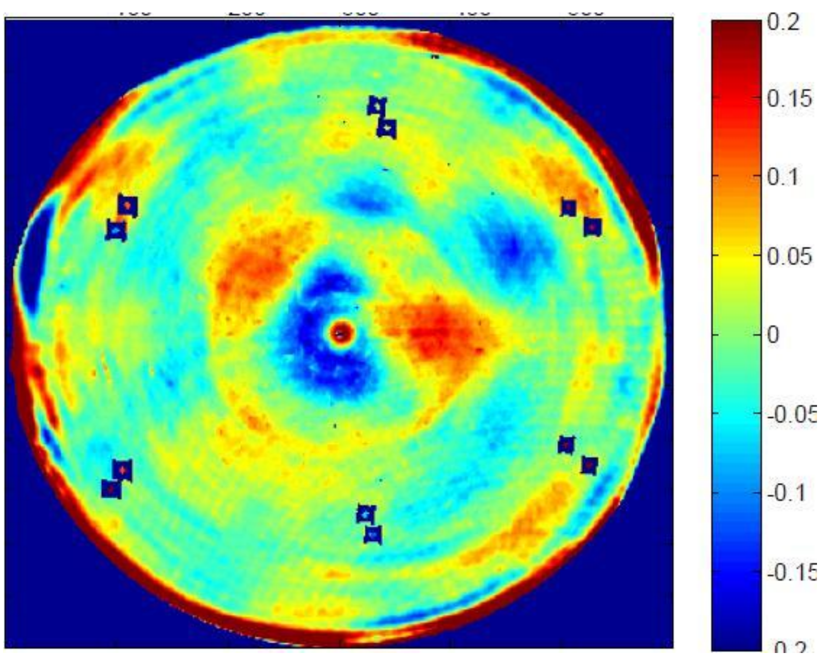
3. SCOTS –measuring 8.4 GMT segment

Transverse ray aberrations are measured; surface slope are calculated; surface sag are integrated with removal of some of the low order shape errors which are sensitive to alignment and camera distortion calibration. Further work is on



Interferometric null test data - LFS , Color scale in micrometers



SCOTS data (LFS to be removed) Color scale in micrometers

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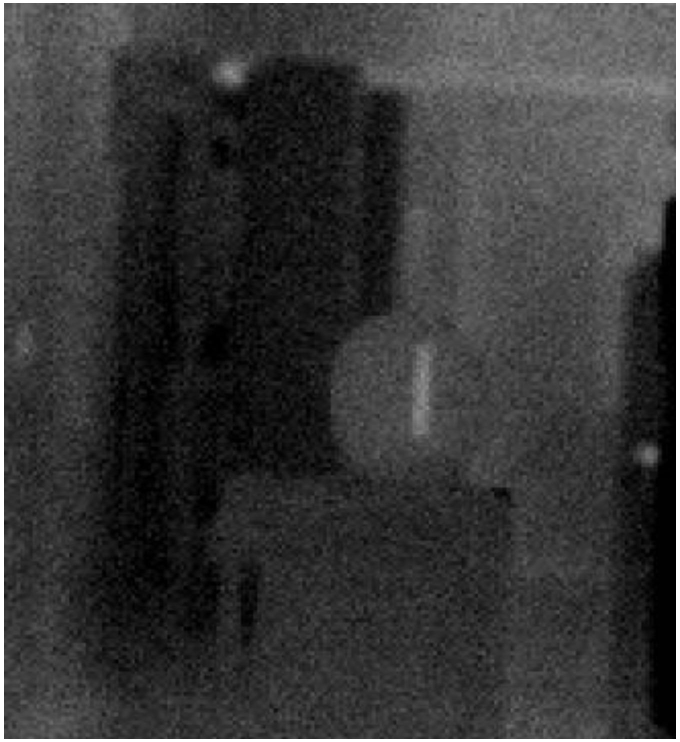
4. SCOTS – In the IR



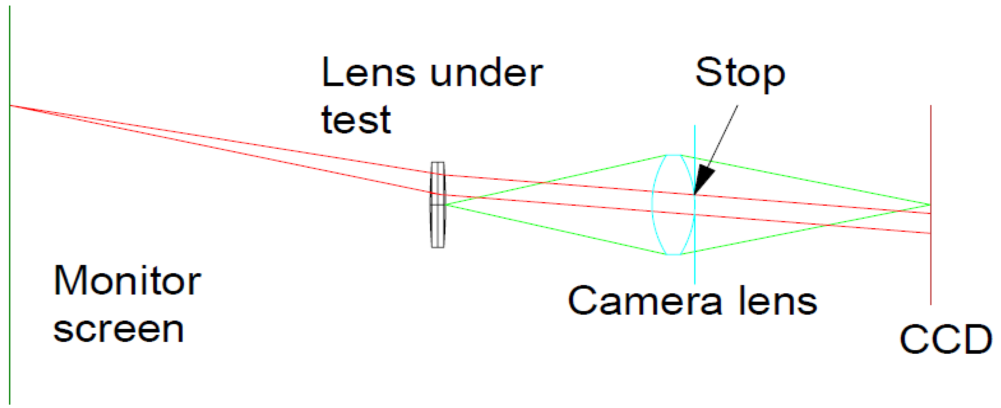
Hot wire source and scanner on orange cart

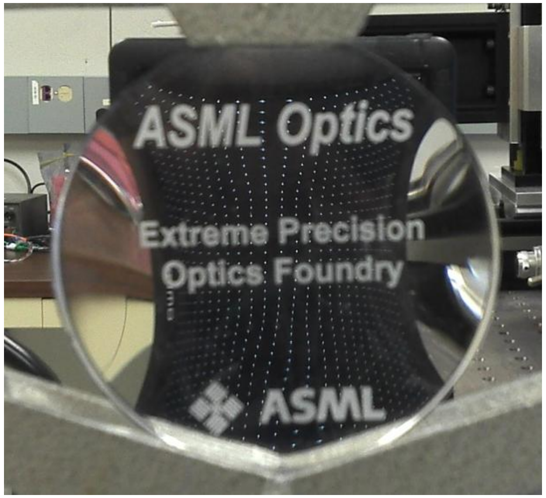
Image of wire on mirror

IR used on ground or rough surfaces to make them look specular,

Slope measurement repeatability in several µrad has been achieved when measuring rough surface grinded with 25 micron grit at 19m distance away.

5. SCOTS – Refractive optics





Screen and camera on opposite sides of lens under test

Camera is focused on lens so pupil is imaged on detector

Camera eye view of uniform array of spots on the screen

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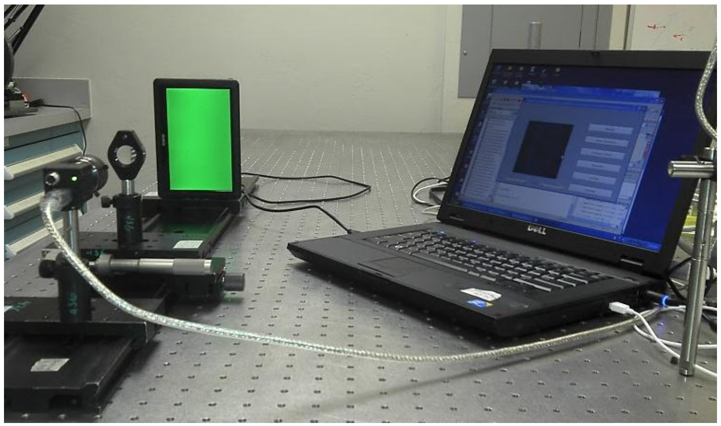
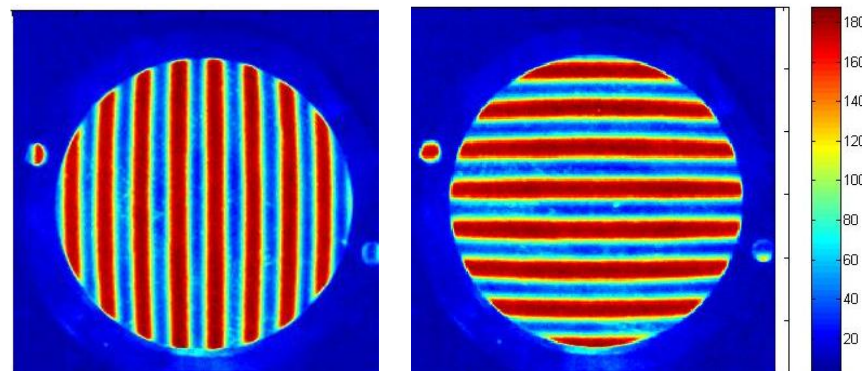
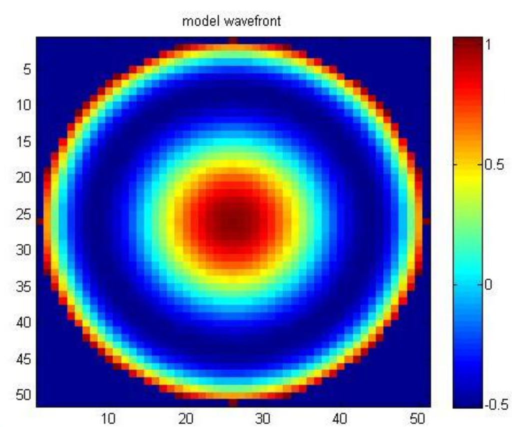
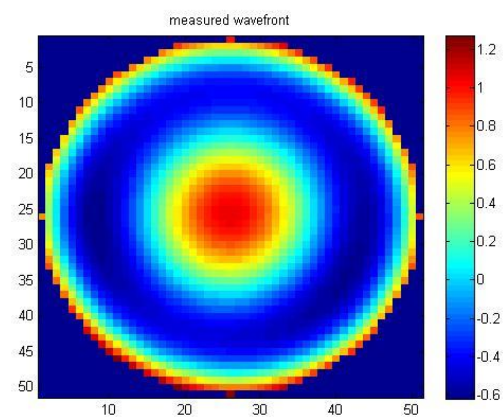
5. Refractive optics example









Test of 75.6 mm efl

Bi-convex singlet, difference comparing with calculation from lens parameters is in nm rms level

6. Summary

SCOTS for precision of optics

1) Reverse Hartmann test model and centroiding slope calculation

2) Modern display technique with the reverse Hartmann test geometry supplies high test dynamic range. The SCOTS can be used for non-null testing.

3) By measuring optical surfaces from their center of curvature, we take advantage of the relaxation for geometric calibration to achieve high measurement accuracy, because the measurement is close to stigmatic.

4) Optimize hardware and algorithms to achieve high accuracy (Dealing with camera pupil aberration effect, using maximum likelihood method[1] to separate system errors, etc)

5) The fundamental method has been known for many decades, it has only been in the last few years that technology has advanced to the point where it is possible to economically implement the method and get wavefront measurements comparable in precision to traditional phase shifting interferometry.

Ref [1]: P. Su et.al. Applied Optics Vol. 49, No.1 p21-31 (2010)

Work funded by Dept. of Commerce, NIST stimulus grant # 60NANB10D010